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Evaluation of the simulations of the North American monsoon in the NCAR CCM3

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Abstract. The six-year average of a ten-year integration of the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3), forced with prescribed, climatological sea surface temperatures, was compared with the Legates-Willmott precipitation climatology and the National Centers for Environmental Prediction (NCEP)-NCAR reanalysis product. Summertime precipitation associated with the North American Monsoon (NAM) circulation is largely underrepresented in simulations using the CCM3. The CCM3 simulates excessive amounts of tropical eastern Pacific and Caribbean precipitation, depressed precipitation over Mexico and the southwestern United States, and largely misrepresents the summertime circulation pattern over North America as compared to the reanalysis climatology fields. Basic diagnostic analyses suggest that excessive convection over tropical waters in the eastern Pacific and the Caribbean alters the summertime circulation pattern which produces excess subsidence over much of Northern Mexico and the southwestern U.S. and prohibits the northward transport of atmospheric moisture into the NAM region. The vertically integrated moisture flux and precipitable water estimated by the CCM3 are significantly different in amount and direction (in the case of fluxes) than those observed in the reanalysis data. Introducing anomalously wet land-surface conditions over the NAM region at model initialization yields minimal improvement. Suspected causes for the erroneous simulation of the summertime circulation in the CCM3 are discussed.

Introduction

The North American monsoon (NAM) is an important hydroclimatologic phenomenon which is prone to intra-seasonal-to-interannual variability and which can bring severe thunderstorms and related phenomena that pose a serious hazard for residents in the southwestern United States and northwestern Mexico [*Douglas et al.*, 1993]. As a water resource the summer rains associated with the NAM are also responsible for over 60% of the average annual rainfall over much of western Mexico [*Higgins et al.*, 1999]. Therefore, it would be of great social and economic benefit to understand the characteristics associated with the average summer rainfall and mean monsoon circulation.

Despite the huge effort that has been made to characterize the salient features of the NAM system, no mechanistic understanding of how the NAM is developed, sustained, and dissipated has yet been offered [*Douglas et al., 1993; Stensrud et al., 1995; Adams and Comrie, 1997; Higgins et al.,* 1997]. One useful way to study the mechanisms of the NAM system is to employ an atmospheric general circulation model and to document its capabilities in simulating the NAM circulation pattern and rainfall by making comparisons with observations. This is a prerequisite to downscaling the GCM-calculated variables using a fine-resolution regional scale climate model.

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Model and methodology

This study uses the latest version of the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3) [*Kiehl et al.*, 1998]. The NCAR CCM3 is a global spectral model with a horizontal T42 resolution (approximately $2.8^\circ \times 2.8^\circ$ transform grid). It has 18 atmospheric layers in the vertical, with the model top at 2.9 mb, and it includes a diurnal cycle with shortwave and longwave radiative fluxes and the radiative effects of clouds calculated every hour. The model time step for this resolution is 20 minutes. Moist convection is represented using the deep cumulus formalism of *Zhang and McFarlane* [1995] in conjunction with the shallow convection scheme developed by *Hack* [1994]. A detailed global assessment of the dynamical simulation of CCM3 is given in *Hurrell et al.* [1998].

The standard land-surface model in the NCAR CCM3 is LSM [*Bonan*, 1996]. The NCAR CCM3 also was coupled to an alternative land model, the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1993]. A summary of the simulations of the land climate in the coupled CCM3 and BATS is given in *Hahmann and Dickinson* [2000], while *Yang et al.* [1999] focused on snow simulations.

In this study, the coupled CCM3-land surface models were integrated for 11 years using monthly climatological sea surface temperature (SST) fields. The results from the time-average of the last 10-year integration are essentially similar to the averages from the last 6 years. The time-average modeled climates for the last six years were assessed relative to the data of *Legates and Willmott* [1990] to assess rainfall, and relative to the National Centers for Environmental Prediction (NCEP)-NCAR global reanalysis data [*Kalnay et al.*, 1996] to assess the atmospheric circulation and moisture fields.

Results

Irrespective of the land surface model used in CCM, the model underestimates zonal mean warm season (July-September) rainfall fields relative to observations [*Legates and Willmott*, 1990] in Arizona and New Mexico (30-35°N) by a factor of eight or greater (Figure 1). To the south and north of this latitudinal band, the model also overestimates rainfall during the warm season. The above statement holds true qualitatively when using precipitation data

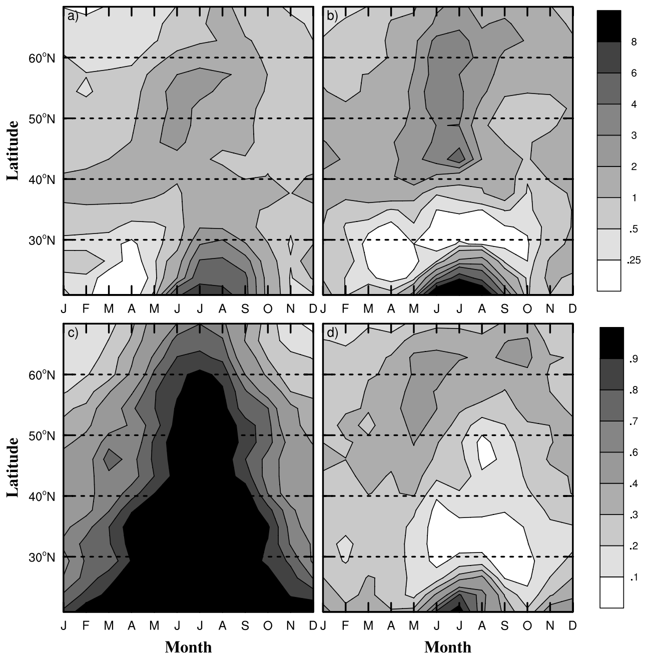

Figure 1. Latitude-month plots of (a) observed precipitation, (b) simulated precipitation from CCM3 coupled with BATS (i.e., CCM3-BATS), (c) ratio of convective to total precipitation in CCM3-BATS, and (d) vertically integrated, random overlap, high cloud amount (400 mb - 50 mb) in CCM3-BATS. The results are shown as zonal averages over land points between 114°W and 104°W.

of *Xie and Arkin* [1996]. The severeness of the summer rainfall underestimation is apparently an artifact due to use of the yearly-repeating climatological SST. With the yearly-varying AMIP SST, the CCM3 produces a much improved simulation of the monsoon rainfall in New Mexico. While the vertically integrated horizontal water vapor transport across the boundaries of the monsoon region (20-40°N, 114-104°W) appear similar during the pre-monsoon months, there are marked differences during the peak monsoon months of July-August (Figure 2). The NCEP-NCAR reanalysis [*Kalnay et al.*, 1996] shows a strong southerly flux across the southern boundary, while the CCM3 simulates a northerly flux. The model also shows a much stronger easterly flux across the eastern boundary compared to the analysis. These results are consistent with the low-level (900 mb) wind vector patterns indicating that lower levels are responsible for greater portions of the overall moisture advection. At the 200 mb level, the reanalysis data indicate that the anticyclonic system is meridionally oriented with a center over western Mexico, but the model shows an eastward displacement of the anticyclonic system which has a zonal orientation (not shown). In addition, there is an overestimation of the moisture convergence over the Gulf of Mexico and tropical oceans that coincides with the overprediction of precipitation in this region. It is realized that the NCEP-NCAR reanalysis may not be perfect, however, the differences seen between the NCEP-NCAR reanalysis and the CCM3 simulations are larger than the differences between the NCEP-NCAR reanalysis and the reanalysis from the European Centre for Medium-range Weather Forecasts (ECMWF) [*Barlow et al.*, 1998].

The underestimated monsoon rainfall in Arizona and New Mexico is consistent with the underrepresentation of deep convective activities. This is evident (Figure 1) from the low values of high cloud between 400 mb-50 mb produced during these simulations when compared with previous studies of deep convection in the NAM [*Douglas et al.*, 1993]. Figure 3 shows that the precipitable water over Mexico and southwest U.S. is less in the model than the analysis by a small factor. This is much smaller than the difference in the modeled precipitation (Figure 1), indicating that the model converts a reduced proportion of precipitable water into precipitation. In the reanalysis, the high values of precipitable water are oriented along the Gulf of California and over the U.S. central plains, while the model displays maximum precipitable water over the tropical eastern Pacific and the Gulf of Mexico.

The core upward motion in the reanalysis data overlies the Sierra Madre Occidental in Mexico, and the southern continental divide and northeastern Great Basin in the U.S. (Figure 3). The stronger upward motions in CCM3 near 15°N over the tropical eastern Pacific, the Caribbean, and the Gulf of Mexico are consistent with an overestimation of the precipitable water and precipitation in these areas, and there is weaker upward motion over Arizona and New Mexico. As shown in the meridional streamfunction plots (Figure 4), CCM3 simulates an overly intense rising branch of the Hadley Cell around 15°N throughout the depth of the troposphere. In addition, the model produces a wide, subsiding branch between 30-40°N. In contrast, the analysis data indicate a weak and shallow rising branch of the Hadley

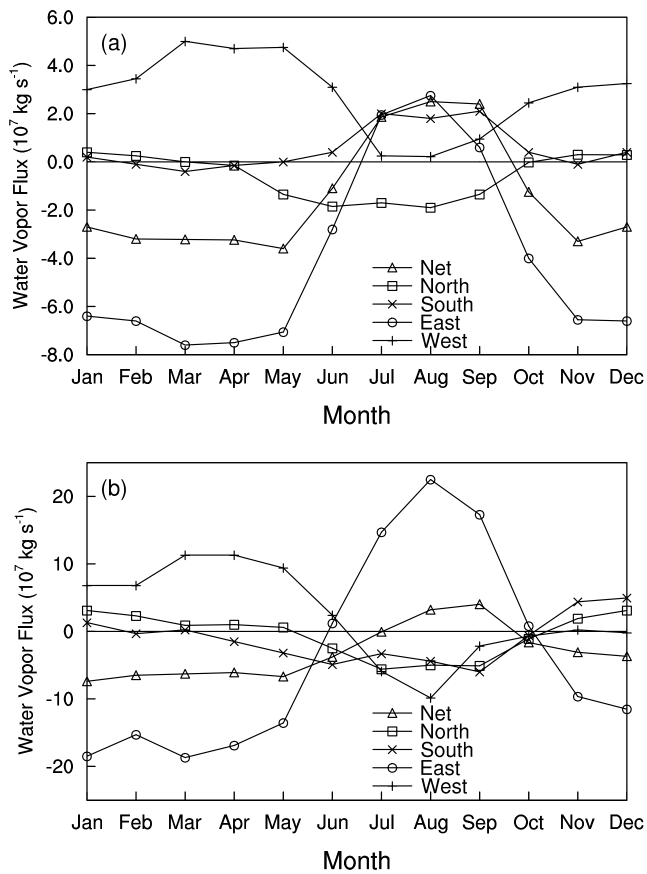

Figure 2. Comparison of vertically integrated vapor fluxes across 20-40°N, 114-104°W from (a) observations and (b) CCM3-BATS.

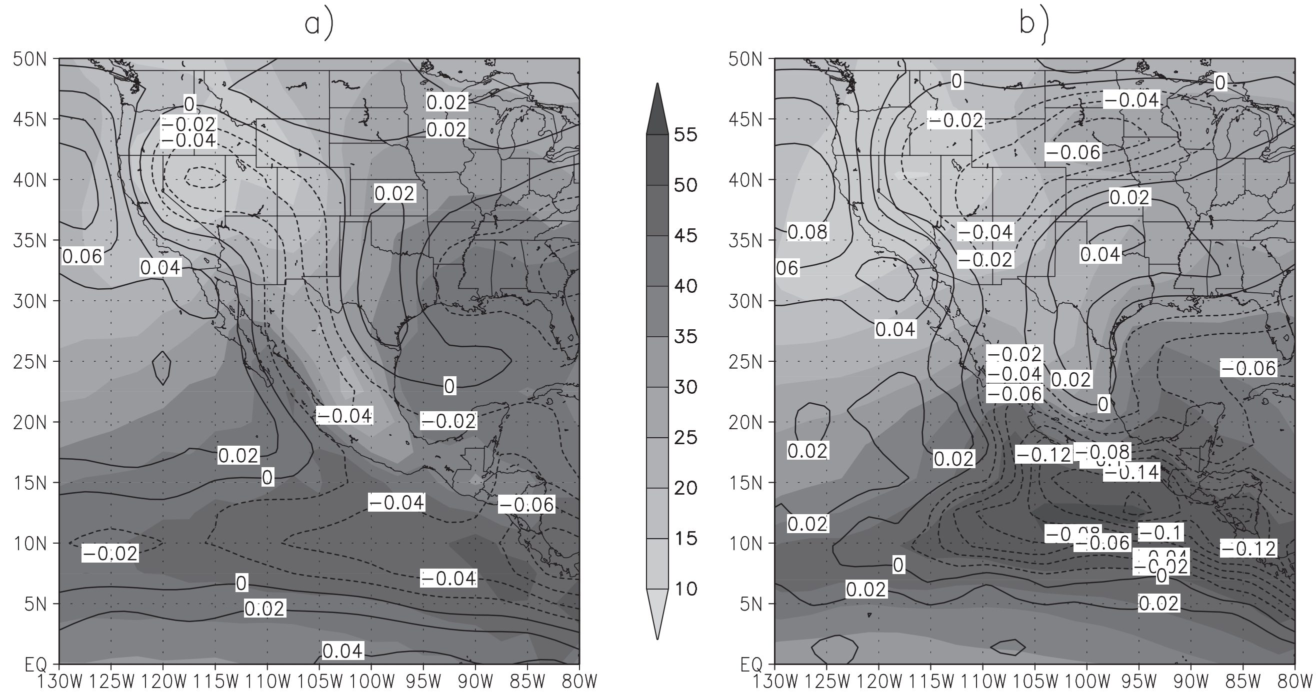

Figure 3. Comparison of July-August-September 600 mb vertical velocity (mb s^{-1}) (contoured) and column integrated precipitable water (mm) (shaded) from (a) NCEP-NCAR reanalysis and (b) CCM3-BATS.

Cell that is confined below 700 mb but which extends from 10°N to 30°N, where the upward motion is found throughout the depth of the troposphere.

Discussion

There are several factors which may be responsible for the above-described distortion of the summertime monsoon circulation and under-representation of rainfall over the southwestern United States. One possibility is that the model simulates overly dry soils over this region. To test this, six integrations were made in which extreme soil-moisture anomalies (i.e., saturated soils) were introduced into the area corresponding to Mexico, Arizona, and New Mexico on May 31 of the last six years of the control run. In each case, the model was then allowed to evolve naturally from June 1 through September 30. The July-August-September (JAS) average precipitation for these six runs was compared to the JAS precipitation average for the (unperturbed) last six years in the control run (Figure 5). The monsoon rainfall is marginally enhanced compared to the control run by introducing this anomalous soil moisture but the model still under-represents precipitation in the southwestern U.S.

The underrepresentation of monsoon rainfall can be significantly reduced by using the yearly-varying AMIP SST during 1979-1988, suggesting the transient SSTs in the extreme years play an important role in contributing to the monsoon precipitation climatology. The simulations of the circulation patterns, however, show little changes compared to the runs from using the yearly-repeating SSTs.

Several other candidate causes are likely also influential in shaping the poorly modeled monsoon circulation. One possible deficiency is the convection scheme used in CCM3. In addition, the T42 resolution used in this study does not resolve the coastlines (e.g., the Gulf of California) and terrain features in the Sierra Madre Occidental Mountains. *Dirmeyer* [1998] showed that the variations in the meridional extent of land in the tropics and subtropics affect the strength of the Hadley Cell and climate over land. These topics are the subject of ongoing investigation.

Summary

The performance of the NCAR CCM3 in simulating the North American monsoon was evaluated by comparing it with the Legates and Willmott precipitation climatology and the NCEP-NCAR reanalysis fields. The model is unable to simulate regional patterns of the monsoon circulation

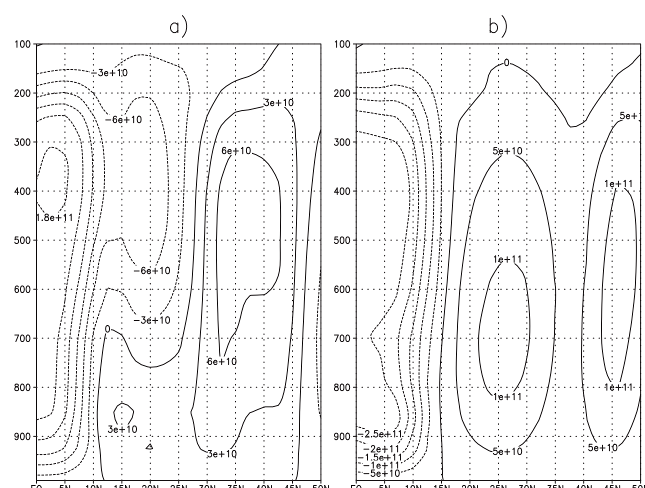

Figure 4. Comparison of July-August-September zonally averaged (130-80°W) meridional streamfunction (kg s^{-1}) from (a) NCEP-NCAR reanalysis and (b) CCM3-BATS.

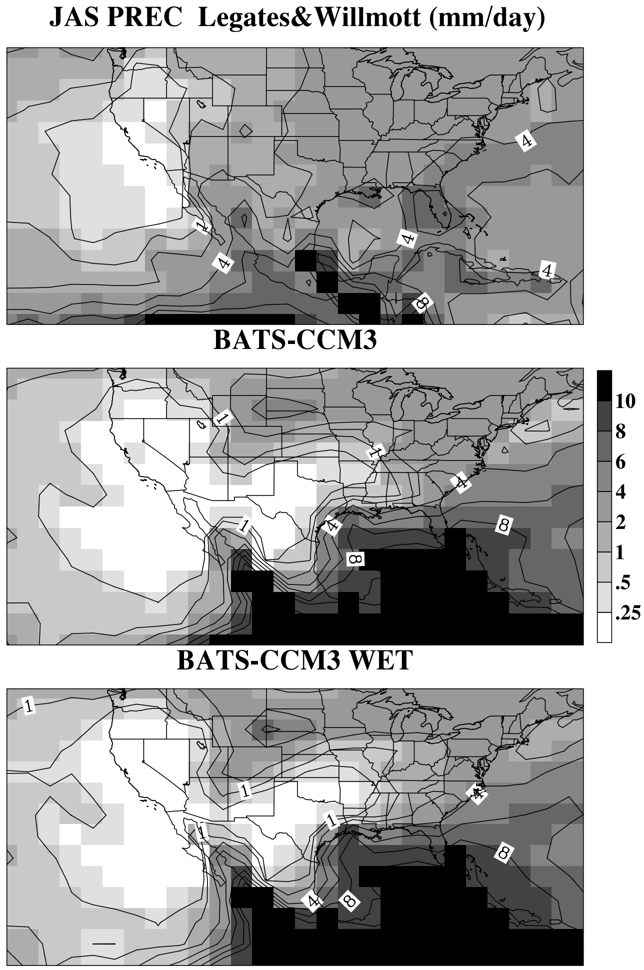

Figure 5. Comparison of mean precipitation in July-August-September (JAS) (mm/day) from (a) observations, (b) the control simulation from the CCM3-BATS, and (c) the wet soil-moisture anomaly simulation with the CCM3-BATS in which the soil moisture was initialized as saturated values over Mexico, Arizona, and New Mexico on May 31. An ensemble run of six members was used to produce the results shown in (c).

and rainfall. The modeled rainfall over the southwest U.S. and Mexico is much too low, while there is overestimation of tropical precipitation in the tropical eastern Pacific and in the Caribbean. Correspondingly, there seems to be an intensification of the Hadley Cell circulation in the model compared to the reanalysis data. The underrepresentation of deep convection in the monsoon region is suggested by the relatively low values of randomly overlapped high cloud, and there are large differences in the vertical motion and precipitable water fields between the model and the reanalysis. The modeled upper level ridge is displaced eastward relative to the reanalysis data in August, and CCM3 simulates a stronger anticyclone at 25-35°N. A sensitivity study that introduced wet soil-moisture anomalies suggests that regional land-surface forcing may play only a marginal role on the large-scale atmospheric circulation. Clearly, further work is needed to define the factors that are shaping the monsoon circulation.

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